its effectors localize to the polarity clusters, and that the UNC-40 receptor itself is required for polarity cluster oscillations. This suggests that the receptor is active even in the absence of netrin, and may itself participate in the posited feedback mechanisms. Given the polarizing roles of netrin/DCC in other cell types, it will be very interesting to see whether similar feedback loops are common in other developmental contexts. More generally, an understanding of the feedback mechanisms in different polarity systems will allow us to appreciate whether they are indeed employed to hone gradient tracking or whether they provide additional benefits.

References

1. Wang, Z., Linden, L.M., Naegeli, K.M., Ziel, J.W., Chi, Q., Hagedorn, E.J., Savage, N.S., and Sherwood, D.R. (2014). UNC-6 (netrin) stabilizes oscillatory clustering of the UNC-40 (DCC) receptor to orient polarity. J. Cell Biol. *206*, 619–633.
2. Ziel, J.W., Hagedorn, E.J., Audhya, A., and Sherwood, D.R. (2009). UNC-6 (netrin) orients the invasive membrane of the anchor cell in C. elegans. Nat. Cell Biol. *11*, 183–189.
3. Teichmann, H.M., and Shen, K. (2011). UNC-6 and UNC-40 promote dendritic growth through PAR-4 in Caenorhabditis elegans neurons. Nat. Neurosci. *14*, 165–172.
4. Adler, C.E., Fetter, R.D., and Bargmann, C.I. (2006). UNC-6/Netrin induces neuronal asymmetry and defines the site of axon formation. Nat. Neurosci. *9*, 511–518.
5. Colon-Ramos, D.A., Margeta, M.A., and Shen, K. (2007). Glia promote local synaptogenesis through UNC-6 (netrin) signaling in C. elegans. Science *318*, 103–106.
6. Hedgecock, E.M., Culotti, J.G., and Hall, D.H. (1990). The unc-5, unc-6, and unc-40 genes guide circumferential migrations of pioneer axons and mesodermal cells on the epidermis in C. elegans. Neuron *4*, 61–85.
7. Huang, C.H., Tang, M., Shi, C., Iglesias, P.A., and Devreotes, P.N. (2013). An excitable signal integrator couples to an idling cytoskeletal oscillator to drive cell migration. Nat. Cell Biol. *15*, 1307–1316.
8. Howell, A.S., Jin, M., Wu, C.F., Zyla, T.R., Elston, T.C., and Lew, D.J. (2012). Negative feedback enhances robustness in the yeast polarity establishment circuit. Cell *149*, 322–333.
9. Sinai, P., Nguyen, C., Schatzle, J.D., and Wulfing, C. (2010). Transience in polarization of cytolytic effectors is required for efficient killing and controlled by Cdc42. Proc. Natl. Acad. Sci. USA *107*, 11912–11917.
10. Das, M., Drake, T., Wiley, D.J., Buchwald, P., Vavylonis, D., and Verde, F. (2012). Oscillatory dynamics of Cdc42 GTPase in the control of polarized growth. Science *337*, 239–243.
11. Bendezu, F.O., and Martin, S.G. (2013). Cdc42 explores the cell periphery for mate selection in fission yeast. Curr. Biol. *23*, 42–47.
12. Hwang, J.U., Gu, Y., Lee, Y.J., and Yang, Z. (2005). Oscillatory ROP GTPase activation leads the oscillatory polarized growth of pollen tubes. Mol. Biol. Cell *16*, 5385–5399.
13. Wu, C.F., and Lew, D.J. (2013). Beyond symmetry-breaking: competition and negative feedback in GTPase regulation. Trends Cell Biol. *23*, 476–483.
14. Tsai, T.Y., Choi, Y.S., Ma, W., Pomerening, J.R., Tang, C., and Ferrell, J.E., Jr. (2008). Robust, tunable biological oscillations from interlinked positive and negative feedback loops. Science *321*, 126–129.
15. Novak, B., and Tyson, J.J. (2008). Design principles of biochemical oscillators. Nat. Rev. Mol. Cell Biol. *9*, 981–991.
16. Meinhardt, H. (1999). Orientation of chemotactic cells and growth cones: models and mechanisms. J. Cell Sci. *112*, 2867–2874.
17. Hagedorn, E.J., and Sherwood, D.R. (2011). Cell invasion through basement membrane: the anchor cell breaches the barrier. Curr. Opin. Cell Biol. *23*, 589–596.
18. Jang, W., and Gomer, R.H. (2008). Combining experiments and modelling to understand size regulation in Dictyostelium discoideum. J. Roy. Soc. Interface *5* (*Suppl 1*), S49–S58.

Department of Pharmacology and Cancer Biology, Duke University Medical Center, Durham, NC 27710, USA.
*E-mail: Daniel.lew@duke.edu

http://dx.doi.org/10.1016/j.cub.2014.09.042

Evolution: A Rapid Flight towards Birds

Remarkable feathered dinosaur fossils have blurred the lines between early birds and their non-avian dinosaur relatives. Rapid skeletal evolution and decreasing body size along one particular lineage of theropod dinosaurs paved the way for the spectacular radiation of birds.

Daniel T. Ksepka

With approximately 10,000 living species, ranging from tiny nectivorous hummingbirds to soaring raptors to secondarily aquatic penguins, birds represent one of the most remarkable vertebrate radiations. How did birds achieve such astonishing diversity? Birds split from their closest living relatives, the crocodilians, approximately 250 million years ago. This deep split places questions about the earliest phases of avian evolution beyond the reach of methods sampling only extant taxa. Thus, evolutionary biologists must turn to the fossil record. An ever-growing trove of fossil theropods — the clade of feathered bipedal dinosaurs that includes such well-known taxa as *Velociraptor* and *Tyrannosaurus* — provides the raw data needed to reconstruct the crucial steps preceding the appearance of primitive birds roughly 150 million years ago. In a recent issue of *Current Biology*, Stephen Brusatte and colleagues [1] harness the fossil record of theropods to provide insight into rates of evolution near the transition between non-avian dinosaurs and birds.

Using an expansive morphological character dataset and methods for estimating rates of evolution, Brusatte and colleagues [1] identify a faster rate of skeletal character change along the theropod lineage leading to birds, as well as a faster rate within birds (as a clade) compared to other theropod clades. Conversely, the study detects no great leap between advanced theropods and basal birds in morphospace (a multidimensional representation of the possible form of an organism, with each axis representing variation of a specific feature). This drives home the message that, although birds represent the endpoint of an exceptional fast-evolving lineage in the theropod evolutionary tree, there is no wholesale morphological transformation on the particular branch leading directly to birds (Figure 1). Rather, the earliest birds were extremely similar to their non-avian theropod contemporaries, and it was after the basic bird 'body plan' was acquired that they began a runaway diversification.

Early Birds

Investigating the evolution of birds requires several pre-requisite steps, including identifying the earliest bird. This is no longer an easy task. For much of the 20th century, the iconic Jurassic fossil bird *Archaeopteryx* seemed to be clearly separated from non-avian dinosaurs. Now, however, the former '*Urvogel*' (original bird) occupies an increasingly crowded and controversial region of the theropod tree. Indeed, several recent studies have garnered fanfare in both the scientific community and the popular media by purporting to 'knock *Archaeopteryx* off its perch'. One recent analysis [2] united the small Chinese feathered dinosaurs *Xiaotingia* and *Anchiornis* with *Archaeopteryx* in a new clade placed deeper in the theropod tree, leaving the bizarre, ribbon-tailed *Epidexipteryx* to inherit the basal bird branch [3]. Strikingly, if *Archaeopteryx* could fly — a subject of debate in its own right — this phylogeny would require two separate origins of powered flight.

However, some character interpretations supporting this hypothesis have drawn criticism [4] and applying model-based optimality criteria to the underlying dataset returns *Archaeopteryx* back to the basal bird branch [5] (though see [6]). Another recent analysis [7] proposed the newly discovered *Aurornis* as a contender for pride of place as the earliest and most basal bird. However, this result clashes strongly with previous phylogenies in many areas, for example placing both the large flightless 'double-sickle-clawed' theropod *Balaur* — widely considered a close relative of *Velociraptor* [1,4,8] — and the Malagasy *Rahonavis* — widely considered to be part of a Southern Hemisphere dromaeosaurid clade [1,4,9] — closer to modern birds than *Archaeopteryx*.

Underpinning the Brusatte *et al.* study [1] is a new phylogeny based on an expansion of the Theropod Working Group project [10], a collaborative effort that has yielded increasingly refined character matrices. Perhaps the most notable aspect of this phylogeny is that it supports a 'traditional' placement of *Archaeopteryx* as a basal bird. *Xiaotingia*, *Anchiornis*, and *Aurornis* are placed in the Troodontidae, and *Epidexipteryx* is pushed down the tree to the Oviraptorosauria. This result suggests *Archaeopteryx* should retain its perch for the time being, though as the authors and others have noted, low support values indicate that many branches near the origin of birds remain unstable [1,2,4,5].

Figure 1. Theropod diversity.

Right to left, the non-avian theropod *Bambiraptor*, the early bird *Zhongornis* and the modern *Gallus* (chicken), three members of one extremely successful evolutionary radiation. Artwork copyright Jason Brougham (www.softdinosaurs.com).

Shrinking Ancestors

Rates of morphological evolution can be quantified using time-calibrated phylogenetic trees. Brusatte *et al.* [1] employ the new phylogeny as the framework for conducting likelihood analyses of skeletal character evolution. These tests recover high rates of evolution both within the bird clade and also along a series of nodes on the theropod 'backbone' leading to birds. In agreement with these results, a recent Bayesian analysis using a different character dataset also found support for a sustained higher rate of skeletal evolution along this backbone [11], though the two studies disagree slightly on how deep in the tree the onset of higher rates occurs. A different set of tests in the Brusatte *et al.* [1] study compares rates between clades, revealing that birds as a clade exhibited a higher rate of skeletal evolution than other theropod clades. As a whole, these results suggest that birds are indeed a special case, leading to the hypothesis that the completion of the avian skeletal plan and development of powered flight opened the door to new ecological niches and triggered a burst of evolution [1].

Body size provides another metric for quantifying rates of evolution, and recent investigations support a distinct trend in size reduction along the theropod lineage leading to birds (Figure 2). Bayesian reconstructions of ancestral body size [11] support a sustained trend of miniaturization across a 50 million year interval leading towards birds, with a high rate of decreasing size evident starting at Neotetanurae (the node where *Allosaurus* and kin branch off from other theropods). Likelihood modeling also supports this general pattern. Another recent study [12] based on a comprehensive dinosaur body mass dataset found evidence for an early burst of rapid size shifts at the beginning of the dinosaur radiation, followed by a general slowdown in size evolution as major clades of dinosaurs became established in their ecological niches [12]. Here again, the lineage leading to birds stands out as an exception, with maniraptoran theropods sustaining high rates of size evolution relative to other dinosaur lineages [12]. A third recent study [13] employing likelihood methods capable of detecting branch-specific rate shifts places the shift to higher rates of size evolution on the branch leading to Paraves (the clade uniting birds, dromaeosaurids, and troodontids). Although these results differ on precisely when body size evolution speeds up, broad consensus is emerging that small size is the result of a long-term trend culminating in breaking through the size limit that enabled powered flight [11–15]. To be clear, this trend is not general to all theropods, as many theropod lineages

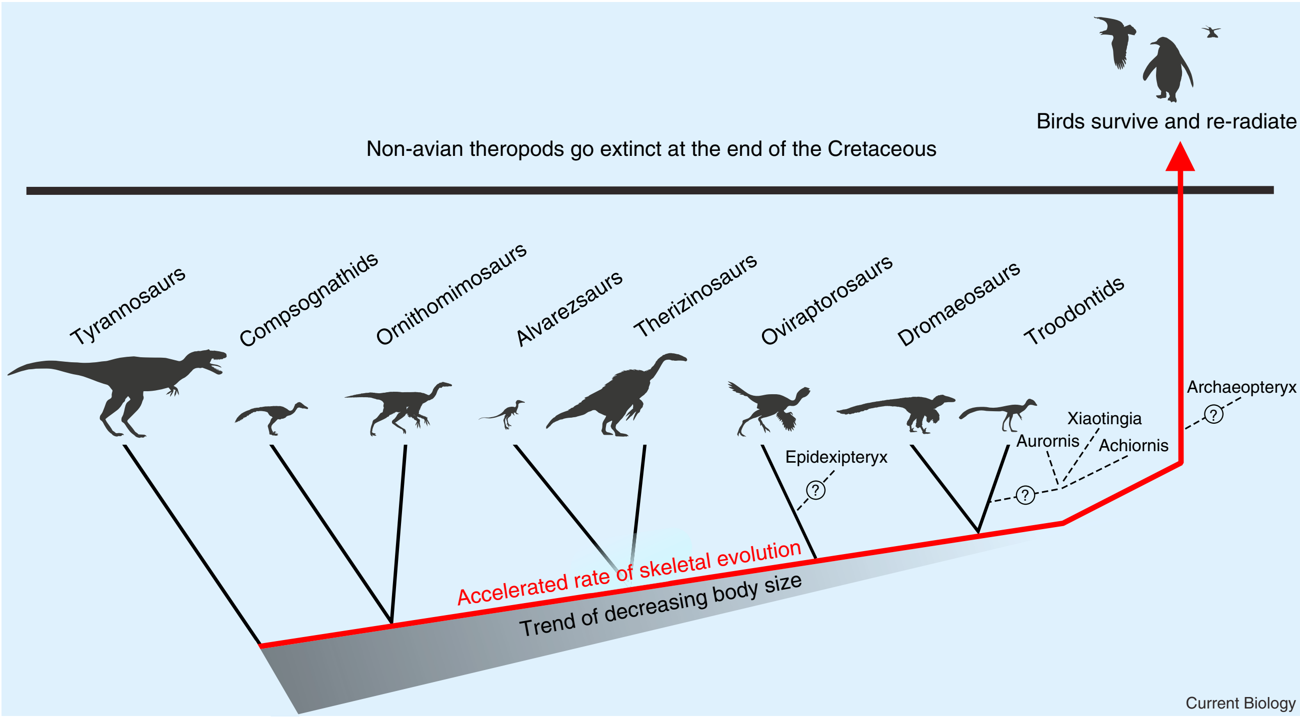

Figure 2. The theropod tree.

Evolutionary tree of theropod dinosaurs, simplified from Brusatte *et al.* [1]. Recent studies demonstrate that the theropod lineage leading to birds exhibited both high rates of morphological evolution and a pervasive trend of decreasing body size. As one approaches the node indicating the divergence of birds from other theropods, uncertainty increases regarding the precise arrangement of feathered theropod species and early birds. Controversial taxa such as *Xiaotingia*, *Anchiornis*, *Aurornis*, and *Epidexipteryx* have recently vied for a position on the bird branch. Silhouettes from phylopic.org by Craig Dylke, FunkMonk, Brad McFeeters, T. Michael Keesey, John Conway, Steve Hillebrand and Steven Traver.

experienced shifts to gigantism while the lineage leading to birds continued its long-term miniaturization [11,12,15]. Ultimately, this shift to small size appears to have had the fortuitous effect of helping birds to survive the Cretaceous-Paleocene mass extinction, which wiped out most large animal species, including all non-avian dinosaurs [11,12].

Although high rates of evolution are inferred on the branches leading to birds, the Brusatte *et al.* [1] study finds that early birds are not significantly distinct from their closest theropod relatives in morphospace (note that in this study morphospace is based on the individual characters of phylogenetic dataset, rather than measurements such as skull length or height). This result will not come as a surprise to those who work on advanced theropods. New fossil discoveries and studies of *Archaeopteryx* have persistently chipped away at the concept that the '*Urvogel*' represents a major leap from its closest non-avian relatives. We now understand that *Archaeopteryx* overlapped with non-avian theropods not only in the shared presence of features once considered unique to birds, such as feathers and a furcula (wish bone), but also in traits such as encephalization and growth rate [14,16–18]. As the lines have blurred, several authors have remarked that a time-traveling naturalist would recognize little if any compelling distinction between basal birds, dromaeosaurids and troodontids [1,4,17]. It is thus no wonder that paleontologists continue to debate the precise placement of taxa like *Xiaotingia* and *Anchiornis*.

Although paleontologists differ in their opinions on finer scale patterns near the origin of birds, the field is coming to a general consensus that birds were the product of an exceptional interval of evolutionary experimentation in theropods. Moreover, the rapid burst of evolution near the Mesozoic origin of birds has a sequel in the Cenozoic. After the Cretaceous–Palaeogene mass extinction wiped out a diverse array of archaic bird species along with dinosaurs and other large animals [19], crown-clade birds not only recovered but radiated into most major extant morphotypes, greatly expanded their overall size range, and achieved a much wider range of ecologies than those inferred for Cretaceous birds [20] in roughly 10 million years.

References

1. Brusatte, S.L., Lloyd, G.T., Wang, S.C., and Norell, M.A. (2014). Gradual assembly of avian body plan culminated in rapid rates of evolution across the dinosaur-bird transition. Curr. Biol. *24*, 2386–2392.
2. Xu, X., You, H., Du, K., and Han, F. (2011). An *Archaeopteryx*-like theropod from China and the origin of Avialae. Nature *475*, 465–470.
3. Zhang, F., Zhou, Z., Xu, X., Wang, X., and Sullivan, C. (2008). A bizarre Jurassic maniraptoran from China with elongate ribbon-like feathers. Nature *455*, 1105–1108.
4. Turner, A.H., Makovicky, P.J., and Norell, M.A. (2012). A review of dromaeosaurid systematics and paravian phylogeny. Bull Am. Museum Natural History *371*, 1–206.
5. Lee, M.S.Y., and Worthy, T.H. (2012). Likelihood reinstates *Archaeopteryx* as a primitive bird. Biol. Lett. *8*, 299–303.
6. Xu, X., and Pol, D. (2013). *Archaeopteryx*, paravian phylogenetic analyses, and the use of probability-based methods for palaeontological datasets. J. Syst. Paleo. *12*, 323–334.

7. Godefroit, P., Cau, A., Dong-Yu, H., Escuillié, F., Wenhao, W., and Dyke, G. (2013). A Jurassic avialan dinosaur from China resolves the early phylogenetic history of birds. Nature *498*, 359–362.
8. Brusatte, S.L., Vremir, M., Csiki-Sava, Z., Turner, A.H., Watanabe, A., Erickson, G.M., and Norell, M.A. (2013). The osteology of *Balaur bondoc*, an island-dwelling dromaeosaurid (Dinosauria: Theropoda) from the Late Cretaceous of Romania. Bull Am. Museum Natural History *374*, 1–100.
9. Makovicky, P.J., Apesteguía, S., and Agnolín, F.L. (2005). The earliest dromaeosaurid theropod from South America. Nature *437*, 1007–1011.
10. Norell, M.A., Clark, J.M., and Makovicky, P.J. (2001). Phylogenetic relationships among coelurosaurian theropods. In New Perspectives on the Origin and Early Evolution of Birds, J. Gauthier and L.F. Gall, eds. (New Haven: Peabody Museum of Natural History), pp. 49–68.
11. Lee, M.S.Y., Cau, A., Naish, D., and Dyke, G.J. (2014). Sustained miniaturization and anatomical innovation in the dinosaurian ancestors of birds. Science *345*, 562–566.
12. Benson, R.B.J., Campione, N.E., Carrano, M.T., Mannion, P.D., Sullivan, C., Upchurch, P., and Evans, D.E. (2014). Rates of dinosaur body mass evolution indicate 170 million years of sustained ecological innovation on the avian stem lineage. PLoS Biol. *12*, e1001853.
13. Puttick, M.N., Thomas, G.H., and Benton, M.J. (2014). High rates of evolution proceeded the origin of birds. Evolution *68*, 1497–1510.
14. Sereno, P.C. (1999). The evolution of dinosaurs. Science *284*, 2137–2147.
15. Turner, A.H., Pol, D., Clarke, J.A., Erickson, G.M., and Norell, M.A. (2007). A basal dromaeosaurid and size evolution preceding avian flight. Science *317*, 1378–1381.
16. Balanoff, A.M., Bever, G.S., Rowe, T.B., and Norell, M.A. (2013). Evolutionary origins of the avian brain. Nature *501*, 93–96.
17. Erickson, G.M., Rauhut, O.W., Zhou, Z., Turner, A.H., Inouye, B.D., Hu, D., and Norell, M.A. (2009). Was dinosaurian physiology inherited by birds? Reconciling slow growth in *Archaeopteryx*. PLoS One *4*, e7390.
18. Clarke, J.A. (2013). Feathers before flight. Science *340*, 690–692.
19. Longrich, N.R., Tokaryk, T., and Field, D.J. (2011). Mass extinction of birds at the Cretaceous-Paleogene boundary. Proc. Natl. Acad. Sci. USA *108*, 15253–15257.
20. Mitchell, J.S., and Makovicky, P.J. (2014). Low ecological disparity in Early Cretaceous birds. Proc. R. Soc. B. Biol. Sci. *281*, 20140608.

Bruce Museum, 1 Museum Drive, Greenwich, CT 06830, USA.
E-mail: dksepka@brucemuseum.org

http://dx.doi.org/10.1016/j.cub.2014.09.018

Vision: Melanopsin as a Novel Irradiance Detector at the Heart of Vision

A recent study defines a novel role of melanopsin-expressing ipRGCs, showing that these inner retinal photoreceptors function as retinal irradiance detectors and provide a local measure of luminance to regulate functional adaptation in the mammalian retina.

Mark W. Hankins* and Steven Hughes

The photopigment melanopsin (Opn4) has come a long way since the end of the last century. What began as a quest to identify the circadian photoreceptor critically led to the discovery of a new class of inner retinal photoreceptor comprising a population of retinal ganglion cells that are intrinsically photosensitive (ipRGCs) [1–3]. These ipRGCs express Opn4 [4], a blue light sensitive opsin protein capable of rendering cells intrinsically light responsive [5]. In the decade that followed their discovery, we have learnt a lot about melanopsin cells and how they provide photic input to the suprachiasmatic nucleus (SCN) and other retino-recipient areas demanding of a robust and highly reliable measure of irradiance. It has been widely assumed that such an irradiance signal is required by the SCN, principally because rod and cone photoreceptors show profound levels of adaption to background light levels and are themselves an unreliable reporter of overall environmental light levels.

Following this analogy it becomes interesting to revisit the classical visual pathway and explore the mechanisms of luminance-dependent adaptation in the retina, a feature that is fundamental to visual function. For many years it was naturally assumed that all light detection in the retina was driven by rod and cone photoreceptors, so that the mechanisms that regulate both photoreceptor and retinal network adaptation were assumed to be driven by these same cells. The emergence of inner-retinal photoreceptors essentially overthrew this dogma and raised the possibility that some of these systems are driven by melanopsin-expressing ipRGCs. The first piece of evidence that this might be the case came from a study of human vision, where it was first shown that a diurnal rhythm in the human cone electroretinogram (ERG) was regulated by a photoreceptor with a melanopsin-like spectral sensitivity [6]. Melanopsin was later shown to be critical in the diurnal and circadian regulation of the mouse photopic ERG [7].

In their latest work, reported in this issue of *Current Biology*, Allen *et al.* [8] present new data on the role of melanopsin in vision, employing an elegant approach that combines the use of a genetically modified mouse, where the spectral sensitivity of cones has been long-wavelength shifted, together with metameric silent substitution to probe the impact of selectively activating or not activating melanopsin during the presentation of photopic visual stimuli. Allen *et al.* convincingly show reversible changes in the photopic flash electroretinogram (ERG) between 'daylight' and 'mel-low' lighting conditions — lighting conditions that activate both classes of cones equally but differ significantly in their activation of melanopsin (while largely saturating rod responses). Under daylight conditions cone ERG responses are reduced at high light intensities, but this adaptive response is lacking under mel-low conditions where activation of melanopsin is selectively reduced. Critically, simultaneous recording in the dorsal lateral geniculate nucleus (dLGN) revealed changes in feature selectivity of visual circuits in both temporal and spatial dimensions depending on levels of melanopsin activation. A substantial fraction of units preferred finer spatial patterns in the daylight condition, while the population of direction-sensitive units became tuned to faster motion. By studying the responses to simple movies they conclude that the dLGN contained a richer encoding of natural scenes when melanopsin was activated.

What are the implications of these phenomena to vision? It has become clear that visual coding is a highly dynamic process and is continuously adapting to the current viewing context